

Holographic Optical Elements as Scanning Lidar Telescopes

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Abstract

We have developed and investigated the use of holographic optical elements (HOEs) and holographic transmission gratings for scanning lidar telescopes. ~~For example, r~~Rotating a flat HOE in its own plane with the focal spot on the rotation axis makes a very simple and compact conical scanning telescope. We developed ~~and tested~~ transmission and reflection HOEs for use at the first three harmonic wavelengths of Nd:YAG lasers. The diffraction efficiency, diffraction angle, focal length, focal spot size and optical losses were measured for several HOEs and holographic gratings, and found to be suitable for use as lidar receiver telescopes, and in many cases could also serve as the final collimating and beam steering optic for the laser transmitter. Two lidar systems based on this technology have been designed, built, and successfully tested in atmospheric science applications. This

technology will enable future spaceborne lidar missions by significantly lowering the size, weight, power requirement and cost of a large aperture, narrow field of view scanning telescope.

Introduction

Lidar is making significant contributions to those Earth sciences requiring remote measurements of atmospheric and surface parameters from ground-based, airborne, and spaceborne platforms. Scanning provides the means for increasing topographical coverage in airborne laser altimeters, and for generating three-dimensional data sets using ground-based and airborne atmospheric lidar systems. Scanning will enable high-density global coverage for observing atmospheric parameters from space, such as cloud and aerosol structure, temperature, and humidity. Of great interest to the atmospheric science community is the possibility for frequent, high vertical resolution, global atmospheric wind profiles. Spaceborne Doppler lidar is currently deemed the most feasible means of obtaining these measurements, and a scanning, pointing, or multiple-look-angle telescope system is required to retrieve full horizontal wind vectors¹. However, most of the scanning atmospheric lidar systems conceived to date have been too heavy and costly to develop into spaceborne versions. Improvements in efficiency, size and weight are required of all technologies involved in lidar remote sensing in order to realize the advantages that lidar offers over passive sensors, such as high accuracy and vertical resolution. Typically, lidars require a large collecting aperture to maximize the laser backscatter signal, and a narrow field-of-view (FOV) to limit the amount of background radiation reaching the detector. In order to scan a conventional lidar system, the entire telescope assembly is steered, or a large flat steering mirror is placed before the telescope to point the FOV in different directions. Focal-plane scanning

approaches have been used in altimetry lidars to scan over several degrees, but are generally not useful for atmospheric lidar requiring scans over 90 degrees or more. NASA is investigating a number of innovative telescope technologies, including deployable optics, ultra-lightweight materials, and the use of diffractive optical technologies for various applications. A large reduction in instrument weight can come from utilizing these new optical receiver technologies individually or in combination.

We have developed and experimentally investigated the concept of a scanning telescope using a holographic optical element (HOE) to help reduce the satellite resources needed for a large, orbiting laser remote sensing instrument for measuring atmospheric parameters: e.g. wind, temperature, and humidity profiles²⁻⁵. By rotating an HOE in its own plane, a conical scan pattern is realized with a minimum of mechanical and electrical requirements. With a single HOE substituting for a conventional telescope primary optic and a scan mirror, the holographic scanning telescope offers advantages over an ordinary scanning telescope by reducing complexity and number of components. When used with a lidar, we transmit the outgoing laser beam through a concave lens f-matched to the HOE, which then collimates the beam while diffracting it at an angle to the HOE. Laser light backscattered by the atmosphere acts as the hologram's reconstruction beam and is focused on the center normal to the HOE. Spinning the HOE about the center normal axis generates a conical scan with the transmitted light and the receiver FOV (Fig. 1). Components from the field stop to the detector remain fixed so no slip rings are required. This makes for a simple compact design.

We also investigated using holographic gratings as scanners in conjunction with static HOEs and conventional telescopes, and find special care must be taken to avoid spurious signals from

the zero and minus-one diffraction orders when these optics are also used to transmit the laser beam.

Review of Scanning Lidars

Conflicting requirements often arise that tend to drive the scanning system design, with cost usually being a major factor. Lidar performance is proportional to both the average power in the transmitted laser beam and the light collecting area of the receiver telescope. Because it is a passive component, increasing the size of the telescope is usually more cost effective than increasing the laser power when it comes to increasing system performance. The instantaneous FOV (IFOV) of these systems is often very small, usually less than 1 mrad, in order to reduce daytime solar background. There are in general three ways of scanning a telescope with conventional optics. One technique is to mount the telescope and associated transceiver optics on a scanning mount. Such mounts are relatively large and expensive in order to accommodate the mass and inertia of the telescope assembly. Astronomical telescopes and tracking mounts are examples of this type. An early example of a lidar employing this type of scanning is the Large Atmospheric Multi-Purpose lidar⁶. More recently, a scanning telescope design was proposed for what would have been the first scanning spaceborne lidar, the Atmospheric Lidar Instrument⁷, but that has since been changed to a non-scanning system due to budgetary constraints.

A second type of scanning telescope utilizes one or more large flat scanning optics in front of the telescope aperture. Examples of single-mirror, single-axis scanning lidars are the Goddard Scanning Raman Lidar⁸, the lidar of Uthe et.al.⁹, and Hwang's terrain mapping system¹⁰. Some systems are designed with a single flat mirror on a two-axis mount. This allows for somewhat more flexibility, including 3-dimensional volume imaging at the expense of a more limited scan-angle range. A somewhat larger flat mirror is also required to scan an equivalent aperture size.

Examples of lidars using single 2-axis scanning flats include the Large Aperture Scanning Airborne Lidar¹¹, and the lidars of Irish and Lillycrop¹², Hawley et. al.¹³, and Bennett et. al.¹⁴. A more compact design uses rotating refractive wedges instead of mirrors to generate a conical scan. The Wind Infrared Doppler Lidar¹⁵ and the Multi-center Airborne Coherent Atmospheric Wind Sensor¹⁶ are examples of this type. The majority of 2-axis scanning lidars utilize two flat mirrors each on its own single-axis mount, in an az-el scan configuration. This usually allows for complete hemispherical coverage in ground-based systems, but is awkward and expensive to incorporate into airborne systems and would be prohibitively large and heavy for spaceborne use. Examples of lidars with two scan mirrors are the University of Wisconsin's Volume Imaging Lidar¹⁷, the system of Hooper and Martin¹⁸, the Raman water vapor lidar of Eichinger et. al.¹⁹, and the Goddard Lidar Observatory for Winds²⁰. Rotating polygon mirrors are sometimes used for rapid scanning in one axis, but these systems are limited in size to smaller apertures and are usually applied in terrain mapping or other hard-target lidars such as the one described by Chen and Ni²¹.

A third major category of scanning lidar telescope using conventional geometric optics involves focal-plane scanning mechanisms. These systems utilize either a small scanning mirror in the focal plane, or an array of detectors combined with separate transmitter beam steering optics. This type of scanning requires a telescope with a total FOV as wide as the angular extent of the scan. Generally, the image plane also needs to be flat and distortion free. This appreciably adds to the cost of a large telescope when the scan angles are greater than a few degrees and is generally limited to altimeters and similar hard-target lidars. The Laser Vegetation Imaging Sensor²² is one example of an airborne scanning lidar that uses a small oscillating galvanometer

scan mirror in the focal plane, coupled with a wide FOV telescope, to achieve ± 7.5 degree cross track scanning.

Holographic Optical Elements

~~The basic treatment of HOE formation, imaging and dispersion properties, including a comparison with conventional imaging optics was covered in the *Handbook of Optical Holography* by Close²³~~ Close²³ covers the basic treatment of HOE formation, imaging and dispersion properties, including a comparison with conventional imaging optics in the Handbook of Optical Holography. In addition to acting as the light collecting objective of a telescope, the HOE can also be used to transmit the laser beam in a lidar system, collimating and steering it at the same time.

The use of HOEs for scanning lasers is not new, nor is the idea of using one as a lidar telescope. Rallison²⁴ conceived of using a static HOE as a spectrally discriminating collecting telescope in a laser range finder. Gilbreath et. al.²⁵ discussed using HOEs as lightweight transceiver optics for collimating and correcting astigmatism in diode laser transmitters for spacecraft optical communication systems. The use of HOEs in laser beam scanners for optical bar code readers is commonplace, with many patents existing in this area. However, most such rotating holographic scanners attempt to straighten out the path of the scanned beam, which would otherwise describe a circle or arc. These systems use small pie-shaped segments of the scanner, each containing a separate HOE to scan the beam at different angles. This makes for inefficient use of the available aperture, which is the opposite design feature required by typical lidar systems, where weak atmospheric return signals necessitate the use of large photon collecting apertures.

The first HOE we designed and constructed to use with a conical scanning lidar was a 40 cm reflection hologram for use with a 532 nm wavelength laser^{2, 26}. Encouraged by the successful demonstration of the concept, we proceeded to develop HOEs for use with other laser wavelengths^{27, 28} and applications. This led to development of the Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE) based on a transmission HOE for use with the 1064 nm wavelength of the Nd:YAG laser²⁹. The use of a transmission HOE allows the system to scan over wide angles through a similarly sized window in the aircraft. We are currently developing holographic telescopes for use with UV (355 nm) wavelengths, 1-meter diameter apertures, and as dispersive optics for Raman lidar applications³⁰. We are also investigating further reduction in mass by eliminating all moving parts^{31, 32} using angle multiplexed HOEs.

Types of HOEs Employed

In our lidar applications we have investigated two categories of HOEs: *reflection HOEs*, in which the incident and diffracted light are on the same side of the HOE, and *transmission HOEs*, in which incident and diffracted light are on opposite sides of the film. Reflection HOEs have the advantage of being able to utilize opaque substrates to support the holographic film or pattern, which opens the possibility of being able to use ultra-lightweight materials such as graphite epoxies and similar composites. Volume phase reflection HOEs must be produced on transmissive optical substrates. After processing, the HOE may be applied to an opaque substrate using film transfer techniques, although these techniques have not been demonstrated for large (~>10 cm) holograms. Reflection HOEs can also be produced as surface relief holograms using reactive ion etching or other techniques operating directly on an opaque substrate. Reflective coatings can be applied to boost the diffraction efficiency.

Transmission HOEs must be applied to optically transmissive substrates such as glass. They are well suited for airborne systems in which one is restricted to having the instrument view through a pressure-sealed window. Placing the receiver HOE very close to the window minimizes the size of window needed to accommodate the wide scan angle. The Bragg planes in reflection HOEs tend to be oriented at oblique angles relative to the optic axis, whereas in transmission HOEs they tend to be oriented at acute angles with respect to the optic axis (which is normal to the film in our examples). Due to this aspect of the fringe-plane structure in transmission HOEs, it is also easier to reduce aberrations to the image quality, allowing one to use a smaller FOV to help decrease daytime solar background levels in lidar telescope applications.

Both types of HOEs are produced by exposing a Solarphire or B270 float glass plate that was spin coated with ~10-micron thick films of dichromated gelatin (DCG) emulsion to two mutually coherent laser beams. HOEs are typically produced with an object beam of spherical wave fronts emanating from a pinhole and plane waves from a collimated beam. The interference of these beams forms a fringe pattern that is recorded in the gelatin during exposure. Photo-induced polymerization takes place where there are bright fringes, creating variations in hardness and index of refraction. Post-exposure processing, oven drying, wavelength tuning, and evaluation of the optical characteristics of the HOE are performed before the film is hermetically sealed with a cover glass.

The development of the first HOE for practical atmospheric lidar applications faced the challenge of making a large (40 cm) diameter optic having both high diffraction efficiency and a small focal spot size. This had to be done using a relatively short focal length in order to design a receiver system compact enough to be competitive with conventional Cassegrain telescopes

typically used in lidar receivers. The final design choice was an $f/3.2$ reflection HOE for use at 532 nm.

The second major step to eventual spaceborne use was developing an airborne lidar system to not only demonstrate the HOE technology, but would also have scientific utility. For this system, a switch to the Nd:YAG laser fundamental of 1064.7 nm was made for measurements of atmospheric aerosol backscatter and terrain mapping lidar applications. Along with the change in wavelength a reduction in the focal spot size was required to utilize the HOE in a lidar system with daytime capability using the small laser pulse energies produced by a diode-pumped Nd:YAG laser. Since the DGC is non-absorbing at the Nd:YAG fundamental the holograms were created with a 488 nm Argon ion laser. Unfortunately, spherical and other aberrations can increase dramatically when holograms are played back at a wavelength well removed from the exposure wavelength. A number of approaches were investigated to overcome these wavelength mismatch aberrations and great success was achieved with "time-reverse ray tracing"²⁷. Once this technique was perfected, the designs for several transmission HOEs were developed and built in rapid fashion for a variety of lidar applications using 770, 1046, 832, 523, and 532 nm light. Many masters and copies of each design were exposed, processed and tested. Master HOEs were generally made to have diffraction efficiencies of 50%, although some were made with high efficiencies intended for end-use. Contact copies are produced by placing an original master HOE in close contact over a glass substrate coated with a fresh layer of unexposed film and its intended cover glass. A fan-shaped sheet of laser light is produced with cylindrical and spherical lenses, then reflected 90 degrees off a long, narrow flat mirror on a mount moving parallel to the HOE to scan the master /copy film (Fig. 2). The scanning laser light passes through the master HOE to the unexposed film. Half of the light is diffracted into the first order,

forming a collimated sheet traveling at an angle with respect to the undiffracted beam with which it interferes to produce the fringes that will expose the copy film.

Optical Performance

The diffractive properties of HOEs make them spectrally dispersive. The dispersion is determined by the surface grating defined by the intersection of the Bragg planes with the surface of the film. To rotate the HOE in its own plane and keep the focus on a fixed point, the output angle must be 0° for the chief ray of the beam. Spectral dispersion helps to filter out background light, since the light at undesired wavelengths is dispersed in the focal plane and will fail to enter the field stop aperture. However, light from different parts of the sky at other wavelengths (within the bandpass of the HOE) will be diffracted into the field stop.

From the ~~well-established~~ well-established coupled-wave analysis developed by Kogelnik, the spectral bandwidth $\Delta\lambda$ for a transmission HOE designed for use at a wavelength λ is

$$\Delta\lambda \approx \lambda d / (T \tan\phi), \quad \text{Eq. 1}$$

and for a reflection HOE is

$$\Delta\lambda \approx \lambda d / T, \quad \text{Eq. 2}$$

where λ the wavelength of the light used to "playback" the hologram, d is the surface spacing of the Bragg-plane fringes. ϕ is the diffraction half-angle, and T is the thickness of the film.³³

The expected efficiency η , of a transmission HOE is given by

$$\eta \approx \sin^2[\pi\Delta n T / \lambda \cos\phi], \quad \text{Eq. 3}$$

and for a reflection HOE by

$$\eta \approx \tanh^2[\pi \Delta n T / \lambda \cos \phi], \quad \text{Eq. 4}$$

where Δn is the peak-to-peak index modulation (the difference between the extremes in index of refraction values in the fringes).

For example, using $\lambda=532$ nm, a typical film thickness of 10 μm , $\Delta n=0.03$, $\theta=45^\circ$, and $\phi=0^\circ$, a transmission HOE will have a peak diffraction efficiency of 89%, and a bandwidth of about 132 nm. Similarly, a reflection HOE with similar parameters will have a peak efficiency of 53% and a bandwidth of 40 nm. The amount of light diffracted as a function of wavelength was measured for the first 532 nm reflection HOE, using a high pressure Mercury arc lamp at the focus of a collimating parabolic mirror to illuminate the HOE. The peak response (uncorrected for lamp output) is at around 528 nm and the spectral bandwidth (FWHM) is about 46 nm, within 15% of the expected value. (Fig. 3) Frequently, bandwidths calculated using Eqs. 1 and 2 do not agree this well with actual bandwidths, because of gradients and chirp (variations in d) in the actual diffractive structure in the HOE. Depending on how a plate is processed, it may play back as if it had 40-80% of the original film thickness because most of the modulation is in the top few microns and not evenly distributed throughout the depth of the film.

Table 1 lists the various HOEs and gratings that were designed, fabricated, and tested as part of this program. Item #1R is the PHASERS reflection HOE made in 1989, described earlier in this paper. Item #2 is a prototype to the HARLIE HOE. Items #3-5 are transmission gratings conceived for use with existing lidars having conventional telescopes. Using improved fabrication techniques developed during this program, #6R was made in an attempt to improve on the efficiency and angular resolution of #1R. Its incident angle was designed to be 43 degrees to match the actual diffraction angle of #1R, in order to replace it in the PHASERS system without having to make any mechanical changes to the lidar. Items 7a, 7b, 8a, and 8b are

designed to be used in pairs for Nd:YLF-based terrain mapping lidars. The a's are transmission gratings that rotate to perform the scanning function, and the b's are transmission HOEs with the collimated beam normal to the optic and the focus off-normal.

We tested the HOEs at their design wavelengths for focal spot size, diffraction angle, efficiency, and focal length using a horizontal collimated beam of laser light at the appropriate playback wavelength, expanded to fill the diameter of the HOE (Fig.4). To correctly orient an HOE to the collimated beam, first the tilt about a horizontal axis along a diameter of the HOE is adjusted so that the specular reflection from its front surface will remain in the horizontal plane. The front surface is identified during manufacturing as the side that a collimated light source should impinge upon to create a focused spot by diffraction. The HOE is then rotated in its own plane about the center normal so that the plane of diffraction is parallel to the table. It is then rotated about a vertical (relative to the table) axis while monitoring the focal spot with a CCD camera, to give the minimum spot size. This requires moving the camera about as the focus location changes with each adjustment, in the horizontal and along the z-axis to accommodate any astigmatism. This establishes the proper incidence angle of the collimated beam with the HOE and the angle of diffraction. We usually find small differences between the incident angle that produces the smallest focal spot and the incident angle that produces the highest diffraction efficiency, but this is usually less than a degree. The spot size is more sensitive than efficiency to departures from the optimum incidence angle, efficiency only changing by 1 or 2 percent over a few degrees. So the optimum angle is the one that produces the smallest spot (Fig. 5). The plane gratings were tested only for diffraction efficiency and diffraction angle.

Diffraction Efficiency

To test the diffraction efficiency of each of the holograms we measured the total energy incident on the HOE and the energy in the first-order diffracted spot. The measurement of the light incident on the HOE was made using a Fresnel lens to collect the light from over the full aperture and focus it onto a 1 cm^2 power meter, as shown in Fig. 4. The same Fresnel lens and meter were then placed on the opposite side of the HOE to measure the diffracted power. We divided the diffracted power measurement by the incident power measurement to calculate the first-order diffraction efficiency. We also measured the zero-order (undiffracted) transmission in this fashion. The test data for the HOEs listed in Table 1 are recorded in Table 2. The percentages in the zero and first orders do not add up to 100 % because some light is lost to scattering, absorption, Fresnel reflections, and other diffraction orders. Item #7a was also tested at 904 nm to see how it might perform if used with a diode laser altimeter system at that wavelength.

The focal lengths were measured with a ruler from the focal point to the center point of the surface of each HOE. The diffraction angle for each grating was measured directly, by retro-reflecting the first order light with a large, flat mirror, and then measuring the difference in angle between the flat mirror and the HOE with a theodolite (Fig. 6).

Different methods were used to measure the diffraction angles of the HOEs. If the HOE was designed with the collimated beam off-normal, the incident (collimated beam) angle was measured using the theodolite in a manner similar to the gratings. If the HOE was designed with the collimated beam normal and the focus off-normal, the diffraction angle of the focus-side optical axis was calculated geometrically using measurements of the focal length and its displacement from the central normal ray.

Spot Size

The focal spot size of each HOE was measured with a CCD camera set in the focal plane of the HOE's. The focal spots were usually slightly astigmatic, with the better HOEs having astigmatic differences of ~1-2 mm. The CCD imaging system software had provisions to calculate the encircled energy as a fraction of the total energy falling on the detector (after a background subtraction) for any size circle or ellipse drawn on the image (Fig. 7). For round looking spots, we found the circle, centered on the energy centroid of the focal spot, that ~~contained~~ contains about 86.5% of the total energy. If the focal spot resembled an ellipse, then the FWHM and $1/e^2$ points were measured for each axis of the ellipse. The encircled energy versus the diameter of such focal plane apertures is plotted for HOEs #1R and 2 in Figs. 8 & 9.

Individual testing and selection of float glass having less than a couple waves per centimeter of flatness error for the construction of the HOEs reduces aberrations induced by the optical quality of the glass to negligible levels for most lidar applications. Rather, the performance is limited by random non-uniformities in the bulk index of the gelatin induced by the chemical processing used to create the index modulation. The process liquids always leave a trail behind as they run off the film following removal from the processing vats. At the surface of the gel these trails are seen as very small surface deformations. Each low spot has under it a higher density of gel than each high spot, so that optical path thickness is constant. Thus, planar wave fronts are not distorted due to refraction by the uneven surface. If a substance with uniform density, like epoxy, is applied to that surface and allowed to fill in all those low spots so that the exit surface is now level, then the time to transit from the bottom of a low spot to the new exit surface has been increased relative to the time to transit from a nearby high spot to the same surface. The result is refraction-induced distortions to the focal spot. This effect is believed to be

the current major source of wavefront errors introduced in light diffracted by the HOE or grating. It typically introduces between 100 and 200 μrad of aberration to the wavefronts.

To minimize this effect in gelatin the processing needs to be improved so that it is more uniform and creates fewer high and low density regions with associated high and low elevations at the surface as well as other volumetric distortions of the fringe structure. Then a cover glass or a layer of epoxy will not create spot enlargement and we expect to see 50 μrad spots, even with a wave or two of error in the recording optics and cover glass. Other sources of wavefront errors include residual spherical aberration and astigmatism not completely corrected in the exposure optical design.

Prototype Lidar Systems based on HOE telescopes

The first system to utilize a scanning holographic telescope system is the Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing (PHASERS). The green reflection HOE #1R is the disk at the far end of the bench at the bottom of Fig. 10. The laser transmitter (1mJ @ 532 nm, 20 pps) is the dark box located on the left, emitting a beam through a diverging lens and a beam tube to a 45-degree turning mirror that directs the beam down and normal to the center of the HOE. The HOE collimates the laser beam while diffracting it up at a 43.5 degree angle from the vertical. At this point the beam is about 4 cm in diameter. The backscattered radiation is collected by the entire HOE aperture and focused to a 2.0 mm field stop located at the top end of the large cylinder supported on the tripod directly above the HOE. The central portion of the HOE that is used to transmit the laser beam is obscured from the detector by the beam turning mirror mount and housing located on the spider assembly just above the HOE.

The HOE is mounted on a rotation stage in order to scan the system. A photon counting photomultiplier detector is mounted in the light colored cylinder directly above the field stop

with a 10 nm interference filter between them to help cut down on stray background light. This system and its early measurements are described in more detail by Guerra et. al. ²⁶. After the initial testing, PHASERS was upgraded with a sturdier mechanical system, improved baffles , a narrower optical filter, and an improved data system, which greatly improved its performance and allowed for successful daytime backscatter measurements.³⁴

The second lidar we built as a technology demonstration to test the utility of using holographic scanning receivers in lidar systems at the 1064 nm Nd:YAG wavelength and in an aircraft environment. The Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE) uses a 40 cm diameter transmission HOE, has a 45 degree diffraction angle and a 1 meter focal length. It scans at rates up to 30 rpm, and can also operate in step and stare or static modes. Improvements to the HOE design and fabrication enabled us to obtain a 200 μ rad focal spot encircling 86.5% of the diffracted energy. The transmitter is a CW-pumped Nd:YAG laser Q-switched at a 5 KHz repetition rate with 200-1000 μ J of pulse energy. The beam is expanded using a -61 mm f. l. lens before being transmitted through the center of the HOE, which collimates the beam to 70 μ rad divergence x 20 mm diameter. The angular divergence of the transmitted beam is smaller than the receiver FOV because the small central portion of the HOE illuminated by the outgoing laser beam introduces fewer wavefront errors than does the full aperture to the backscattered light. Additional details and measurements made with the HARLIE system are described by Schwemmer²⁹, Wilkerson et.al.^{35, 38}, Schwemmer et.al.³⁶ and Sanders et.al.³⁷ and on the HARLIE web site³⁹.

Practical Considerations

After extensive testing and field use of various configurations of holographic gratings and HOEs for lidar applications as the primary transceiver optic, we have some additional insights into the benefits and limitations of these devices. First, for either HOE type the collimated beam cross-sectional area (transmitted and received) is an ellipse, with the effective lidar receiver collection area reduced from the actual HOE area by the cosine of the diffraction angle.

Secondly, the HOEs constructed we produced and employed work without any ill effects when used with moderate power, low energy Q-switched lasers at wavelengths not absorbed by the materials used. The HARLIE laser illuminates the central 2 cm diameter of the HOE for an average energy density of 65-320 $\mu\text{J}/\text{cm}^2$ and average power density of 0.32-1.6 W/cm^2 . The green PHASERS laser (1 mJ, 20 ns, 2 kHz) has also been used without any apparent degradation in the HOE performance over time. Even several years in an uncontrolled (but enclosed) environment and many hours of exposure to direct sunlight have not had any noticeable effect on its performance. However, when a small holographic grating was illuminated with the unexpanded output of a large pulse (600 mJ, 10 nsec) of a 532 nm Q-switched Nd:YAG laser having an energy density of $\sim 1 \text{ J}/\text{cm}^2$, the absorption from the traces of residual dichromate and the epoxy used to encapsulate the HOE with a cover glass was sufficient to cause catastrophic optical damage.

Thirdly, boresight alignment between the laser and the HOE is essentially the same as for a lidar using a conventional telescope. For a coaxial or parallel transmitter-receiver alignment, one wishes to make the laser appear to emanate from the field stop when viewed looking back into the lidar from infinity. If the field stop is not positioned exactly on the rotation axis, the scan will still describe a cone, but the axis will be tilted slightly with respect to the HOE rotation axis.

Fourthly, one expects to have some polarization dependence of the diffraction efficiency in an HOE. In order to match the diffraction efficiency of s and p polarized light, one needs to control the average index and the index modulation values during the HOE manufacturing process⁴⁰. One has to sacrifice peak efficiency for either polarization in order to achieve equal polarization at the design wavelength and diffraction angle. The point at where both polarizations are equal is about 85%. It is very difficult to control the manufacturing process parameters accurately enough to exactly match the efficiency for both polarizations. Typically there will be a few-percent difference between them. And because the diffraction angles vary over the surface of the HOE, there is a modest dependence of the diffraction efficiency over different areas of the HOE.

Fifth, gelatin is an elastic material and conforms to any substrate to which it is applied. When the substrate changes size due to temperature changes, the holographic film will follow. The primary effect is a change in the surface grating pitch on each surface of the film. This surface grating is what determines the optical geometry, *i.e.* the focal length and the diffraction angle will both change in direct proportion to the expansion rate of the substrate. A typical thermal expansion coefficient for glass of $\sim 10^{-5} \text{ K}^{-1}$ yields a change in diffracted angle of about $\sim 15 \text{ } \mu\text{rad/K}$ and a change in focal length of $\sim 10 \text{ } \mu\text{m/K}$ for the HOEs used in our lidars. The latter is of little consequence given the depth of field of an $f/2.5$ lens. The diffraction angle change will basically change the cone angle of the scan pattern. As long as the transmitter and receiver field stops are built with an athermal mechanical design, boresight alignment should not be detrimentally affected. Barring any large thermal gradients across the HOE optic, the transmitted beam and the receiver FOV track together.

Lastly, we also experimented with using holographic transmission plane gratings placed in front of a conventional telescope to generate the conical scan. This technique has one disadvantage over using an HOE to perform the scanning if the grating is also used to transmit the outgoing laser beam. The ~2-5% of undiffracted zero-order light constitutes a second collimated transmitted beam which will generate its own return signal that will be collected and combined with the main return signal from the +1 diffracted order (Fig. 11a). On its return, the backscattered light does not meet the Bragg condition for diffraction in the grating and passes through relatively unattenuated. If there are any clouds in the zero-order beam path, their backscatter signals may be comparable in magnitude to that of cloud-free regions of the main beam path and will be superimposed on the main signal. To make matters worse, the two signals will have a different range-altitude relationship that depends on the pointing direction and orientation of the lidar. Using a baffle tube for transmitting the beam after it leaves the grating in order to block the transmitted zero-order light can alleviate this problem. However, this baffle will have to be attached to the rotating optic in order to steer with the laser beam, adding to the mechanical complexity of the system. Alternatively, the laser can be transmitted using mirrors or prisms mounted in a fixture attached to a hole through which the beam passes, cut in the center of the grating.

This "cross-talk" is not a problem in the HOE based telescope. The zero-order transmitted beam continues to diverge after leaving the HOE. Atmospheric backscattered light from the 0-order transmitted beam fails to match the Bragg condition and is not diffracted to a focus in the telescope (Fig. 11b). It is also best to use a design in which second order is evanescent. For an HOE in which the focal side axis is normal to the optic, then the collimated side diffraction angle should be 30 degrees or more to eliminate higher diffraction orders

Summary and Conclusions

We have shown that large HOEs can be used effectively as conical scanning lidar telescopes that are mechanically much simpler and more compact than designs using conventional telescopes and scan optics. When an HOE is made with a point source object beam diverging and normal to the film, and a collimated reference beam at some angle to the film, the object beam defines the focal length and the rotation axis for scanning, while the reference beam defines the scan cone half-angle. A conical scan pattern is generated when the HOE is rotated in its own plane about the optic axis that goes through the focal point. Low energy density laser pulses can be transmitted through the HOE, which acts as the final collimating and beam steering optic. Two prototype lidar systems, one using a reflection HOE with a 532 nm laser transmitter, and one using a transmission HOE with a 1064 nm laser transmitter have been built and successfully tested. Angular resolutions as small as $180 \text{ } \mu\text{rad}$ have been obtained, allowing HOEs to be used as small FOV receivers. Holographic plane gratings can also be used to conically scan conventional telescopes or static HOEs provided care is taken to suppress possible zero and negative first order diffracted light, especially if the grating is also used to scan the outgoing laser beam. Several years of use have shown the HOE assemblies to be robust and reliable. Future developments include scaling to meter apertures and larger, increasing angular resolution, and multiplexing HOEs to utilize multiple wavelengths or multiple fields of view so as to negate the need to move the HOE in order to scan.

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NASA Goddard Technology Commercialization Office, Lisa Callahan of the NASA Cross-Enterprise Program, and Steve Mango of the Integrated Program Office. We thank Barry Coyle for helping to design and build the first laser for PHASERS, Steve Palm for developing the first PHASERS data acquisition software, Kurt Medine, Wayne Welch, and Jeffrey Freemire for PHASERS mechanical design support, Alex Leung for HOE testing, Orbital Sciences Corporation and Science and Engineering Services, Inc. for HARLIE engineering, fabrication, and HOE testing. Special thanks go to David Miller for his help deploying and operating HARLIE and to Sangwoo Lee for help in acquiring and analyzing the HOE test data.

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Figures

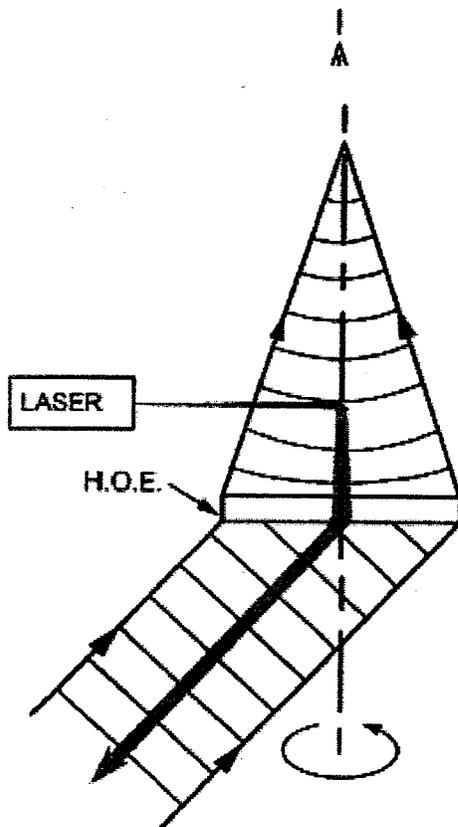


Fig. 1. Geometry for using a transmission HOE to scan the transmitted laser as well as the receiver FOV.

Fig. 1. Exposure geometry (a), and reconstruction geometry (b) for a reflection HOE.

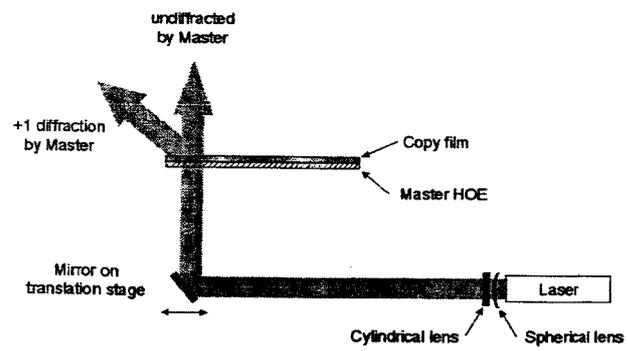
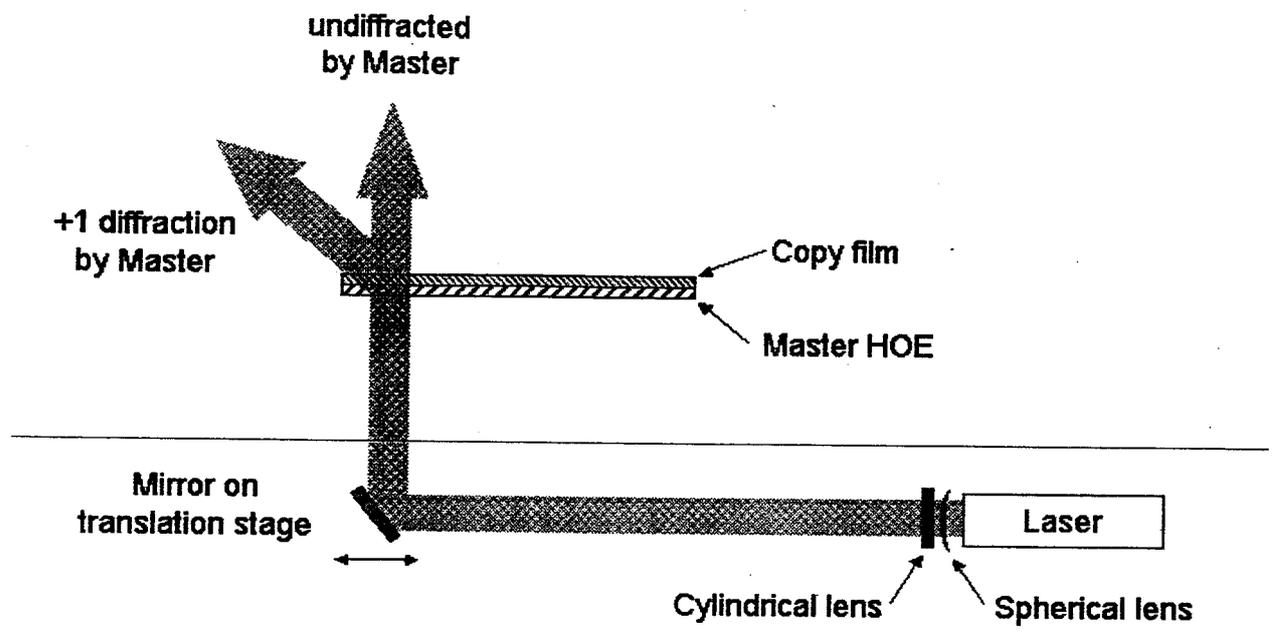


Fig. 2. Copying an HOE from a master. The laser beam is formed into a sheet (perpendicular to the paper) before scanning the master/copy assembly.

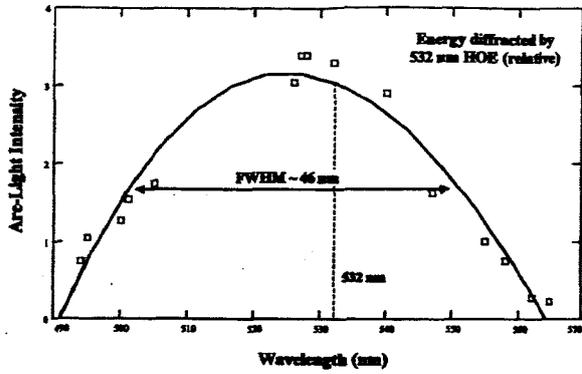


Fig. 34. Relative spectral response of HOE #1R.
The curve is a spline fit to the data points.

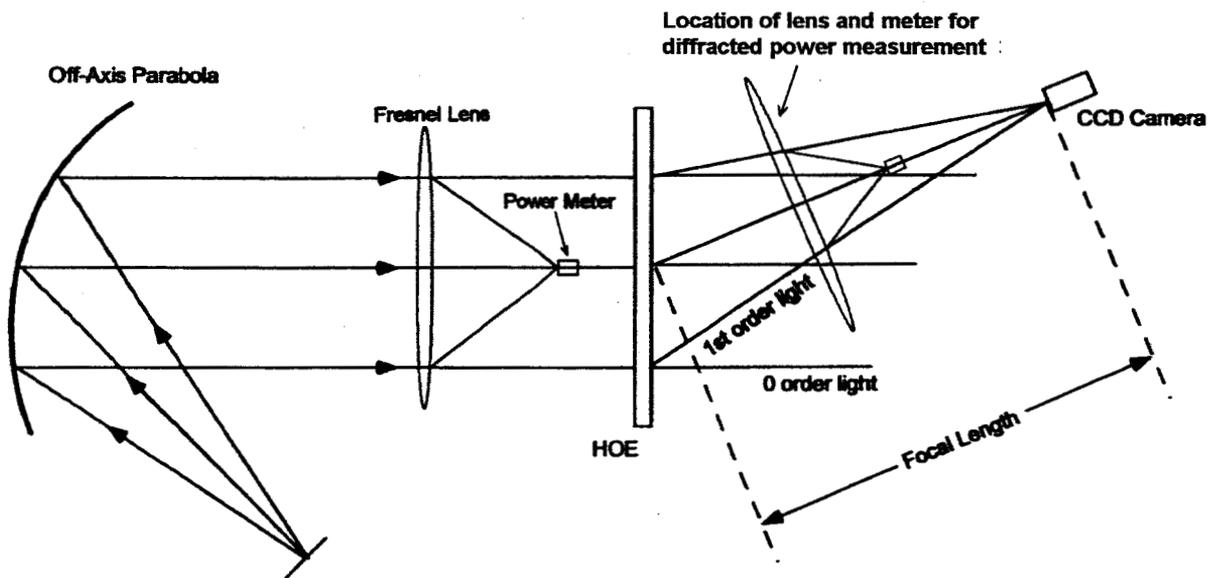


Fig. 45. Setup for measuring diffraction efficiency and spot size.

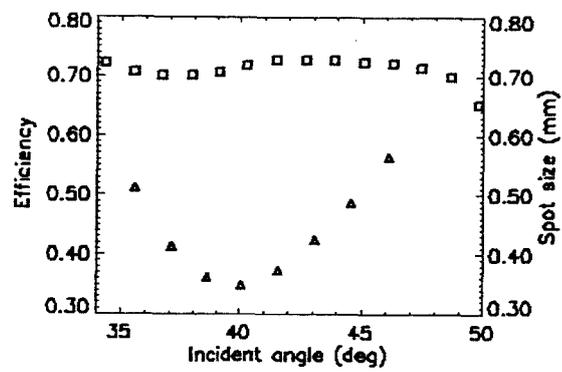


Fig. 56. Diffraction efficiency (squares) and spot size (triangles) as a function of incident angle for HOE#7R.

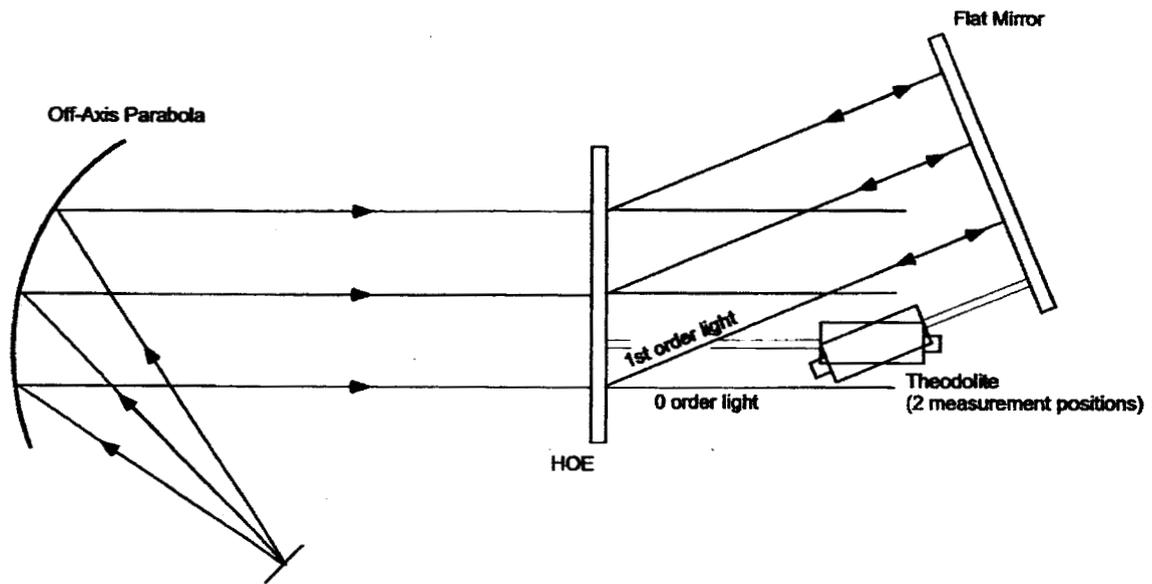
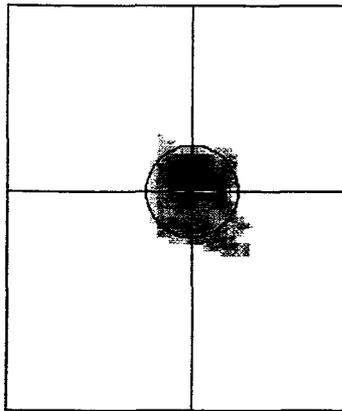


Fig. 67. Grating diffraction angle test setup.

COLOR TABLE

16 Levels
235-251+
220-234+
204-219+
188-203+
173-187+
157-172+
141-156+
126-140+
110-125+
94-109+
78-93+
63-77+
47-62+
31-46+
16-30+
0-15+



Contouring Mode = Automatic Scaling to Peak

Fig. 87. CCD camera image of focal spot of one of the preliminary copies of HOE #2. The reticle circle diameter is 270 μ m.

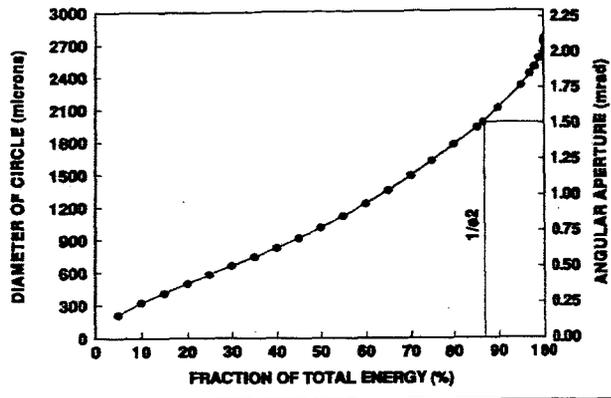
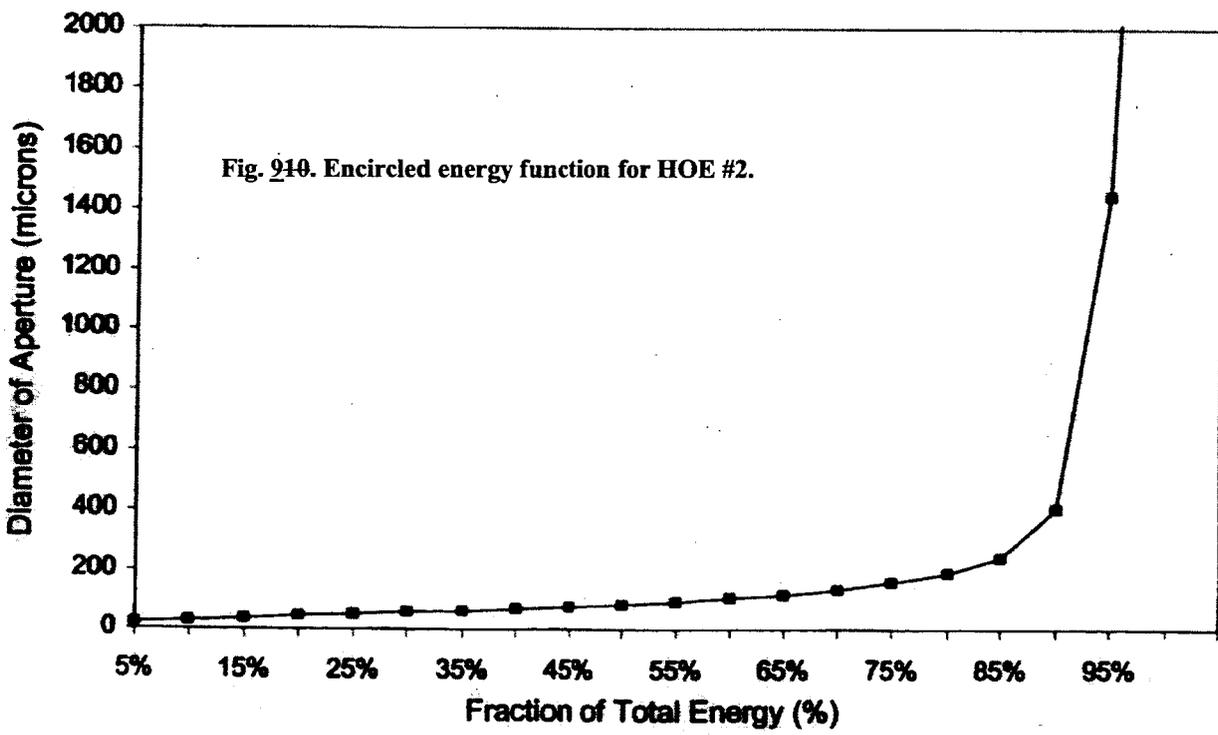
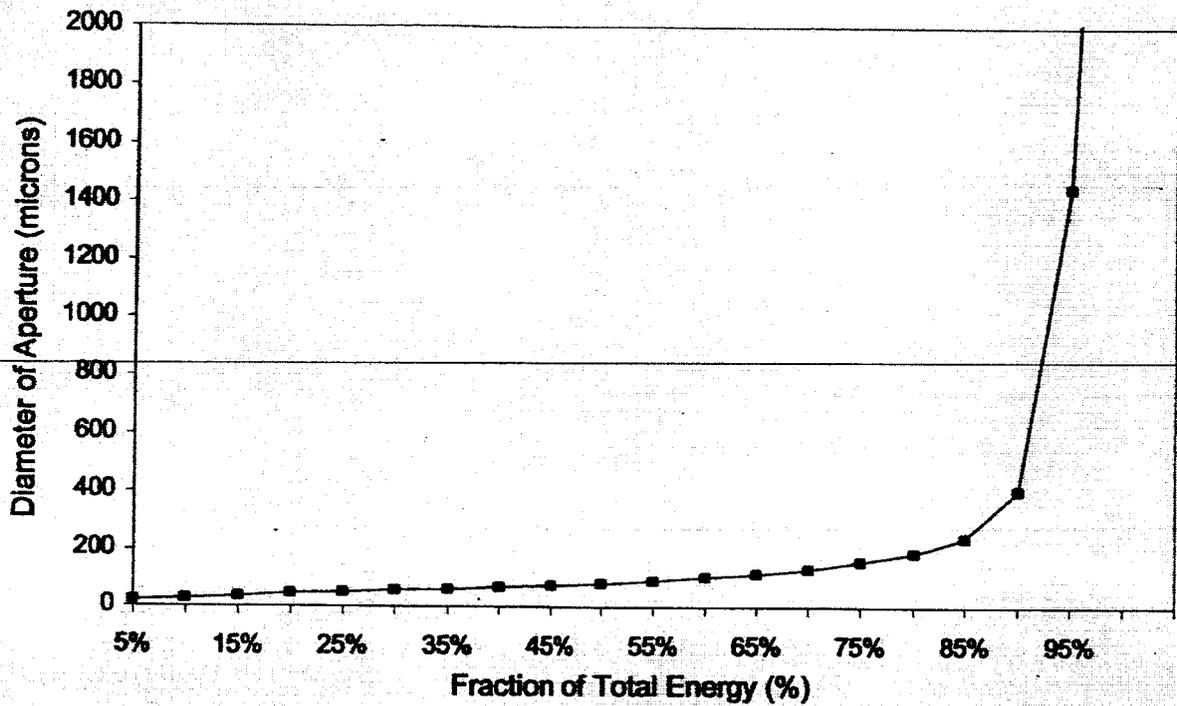


Fig. 89. Encircled energy function of focal spot for HOE #1R.





PHASERS ASSEMBLY

Fig. 120. Mechanical drawing of the new PHASERS transceiver.

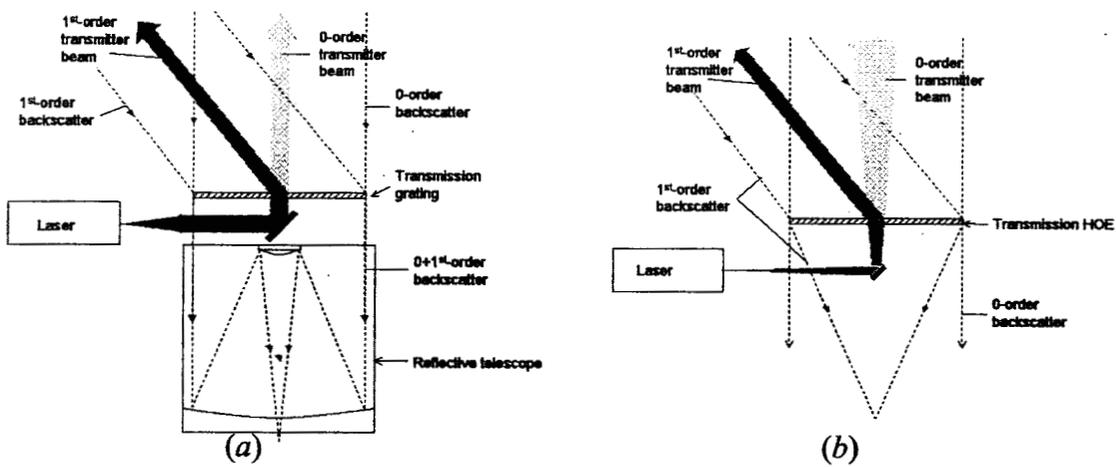


Fig. 161. a) Crosstalk from the 0-order beam is focused in a conventional telescope used with a grating scanner. **b)** Crosstalk from the 0-order beam is not focused in an HOE telescope.

|

Figure Captions

~~Fig. 1. Exposure geometry (a), and reconstruction geometry (b) for a reflection HOE.~~

Fig. 1. Geometry for using a transmission HOE to scan the transmitted laser as well as the receiver FOV.

Fig. 2. Copying an HOE from a master. The laser beam is formed into a sheet (long dimension is into the paper) before scanning the master/copy assembly.

~~Fig. 3. Geometry for using a transmission HOE to scan the transmitted laser as well as the receiver FOV.~~

Fig. 34. Relative spectral response of HOE #1R. The curve is a spline fit to the data points.

Fig. 45. Setup for measuring diffraction efficiency and spot size.

Fig. 65. Diffraction efficiency (squares) and spot size (triangles) as a function of incident angle for HOE#7R.

Fig. 67. Grating diffraction angle test setup.

Fig. 78. CCD camera image of focal spot of one of the preliminary copies of HOE #2. The reticle circle diameter is 270 μm .

Fig. 89. Encircled energy function of focal spot for HOE #1R.

Fig. 919. Encircled energy function for HOE #2.

~~Fig. 11. Early version of the first atmospheric lidar using a scanning reflection HOE.~~

Fig. 102. Mechanical drawing of the new PHASERS transceiver.

~~Fig. 13. HARLIE system transceiver (left) and data system (right).~~

~~Fig. 14. Position of HARLIE in an aircraft, suspended from the floor.~~

~~Fig. 15. A scan of ground based HARLIE backscatter data taken the night of 9 June 1999, during the HOLO-2 campaign (Wilkerson et.al., 2001).~~

Fig. 116. a) Crosstalk from the 0-order beam is focused in a conventional telescope used with a grating scanner. b) Crosstalk from the 0-order beam is not focused in an HOE telescope.

~~Fig. 17. Two methods of wavelength multiplexing HOEs to maintain static detector assemblies. a) The foci are all placed on the rotation axis. b) A rotating plane grating scanner followed by a static multiplexed HOE.~~

Table 1

Table 1. Partial List of the HOEs and gratings manufactured and tested in this program.

Item # [†]	Wavelength (nm)	Diameter (mm)	Focal Length (mm)	Angle 1	Angle 2*
1R	532	404	1300	45	0
2	1064	404	1016	45	0
3	1064	404	∞	45	0
4	770	404	∞	45	0
5	532	404	∞	36	0
5R	532	404	1295	43	0
6a	1047	202	∞	22.5	0
6b	1047	202	760	0	22.5
7a	1047	254	∞	22.5	0
7b	1047	254	760	0	22.5

[†] An R following the number indicates a reflection hologram, otherwise it is a transmission hologram.

* For HOEs, angle 1 refers to the collimated beam axis and angle 2 refers to the focusing axis, relative a normal to the substrate.

Table 2

Table 2. Test measurement results for holographic optics of table 1.

Item #	Focal lengt h ± 2 (mm)	Spot size 1/e ² * (μrad) ± 5%	Spot size FWHM (μrad) ± 5%	Zero order efficiency ± 0.2 (%)	1 st order efficiency ± 2 (%)	Diffraction angle ±0.1 (degrees) for smallest focal spot	Comments Errors are given column in headings unless otherwise noted.
1R	1295	1200			59	42.0±0.5	PHASERS HOE
2	1016	180		5	86	45.0	HARLIE HOE
3	N/A	N/A	N/A	9.5	73	45.0	
4	N/A	N/A	N/A	7	84	45.0	
5	N/A	N/A	N/A	13	74	36.4	
6R	1306	630	350	~3	73	40.1	~7% specular reflections from internal surfaces.
"	1306	486	269		72	40.1	The best focus occurred at this angle.
7a	N/A	N/A	N/A	1.3	91	22.8	
"	N/A	N/A	N/A	11	76	20.3	
@904nm							
7b	756.2	225 x 262	56 x 138	7.4	84	23.2	
8a	N/A	N/A	N/A	2.9	90	22.1	
8b	760.1	135 x 285	43 x 149	6.4	86.5	22.7	

* If two numbers are given they describe the major and minor axis of an ellipse, if one number it describes a circle. Either conic contains 86.5% of the energy diffracted into the first order.

Table Captions

Table 1. Partial List of the HOEs and gratings manufactured and tested in this program.

Table 2. Test measurement results for holographic optics of table 1.

Popular Summary

Holographic Optical Elements as Scanning Lidar Telescopes

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NASA has developed new telescope systems that use holograms instead of lenses or mirrors. These holographic telescopes were developed in an effort to reduce the size, weight and cost of laser instruments used to measure atmospheric properties like temperature and wind. Several hologram designs were made and tested in the laboratory. Two were incorporated into laser remote sensing systems that are used on the ground and in airplanes to study the atmosphere. Our goal is to enable the development of spaceborne scanning laser remote sensors for Earth science applications using the lightest and least costly technologies available.